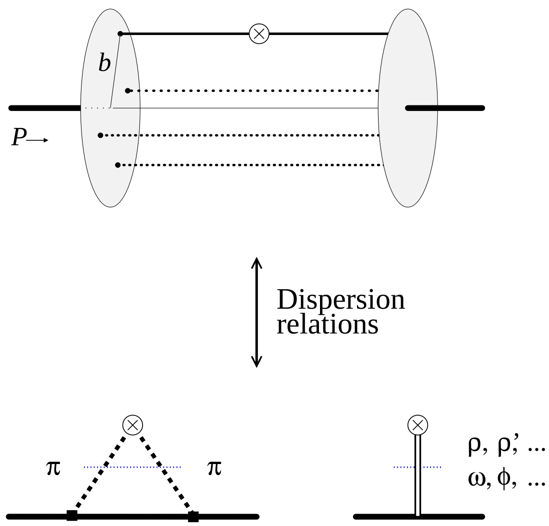
Partonic structure meets meson exchange: Exploring duality with transverse densities

C. Weiss (JLab), Bonn U. HISKP Colloquium, 04–Jul–13



- Nucleon structure in QCD

  Why parton picture

  Transverse densities from elastic FFs

- Spectral analysis of transverse densities

  Dispersion representation of densities
  Strikman, CW, PRC82 (2010) 042201

  Large distances $b \sim 2\,\text{fm}$: Chiral dynamics

  Intermediate $b \sim 1\,\text{fm}$: Vector mesons
  Miller, Strikman, CW, PRC84 (2011) 045205

  Partonic interpretation

- Pion transverse charge density

  Timelike FF from e^+e^- data:
  Pointlike $q\bar{q}$ configurations
  Miller, Strikman, CW, PRD83 (2011) 013006

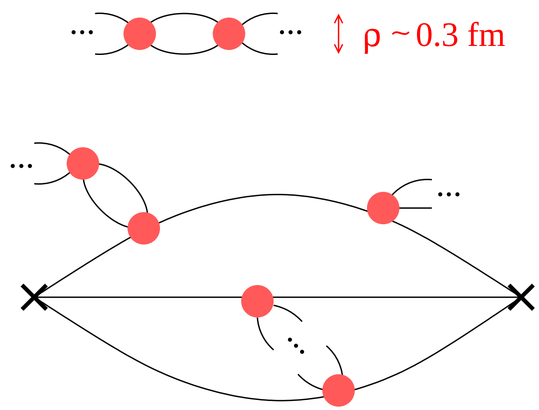
- Outlook: GPDs, new data

Express pion cloud, vector meson dominance in QCD!

Explore parton–hadron duality in t–channel kinematics!

Understand spatial structure of nucleon as relativistic system!

Nucleon structure: Parton picture



- QCD vacuum not empty

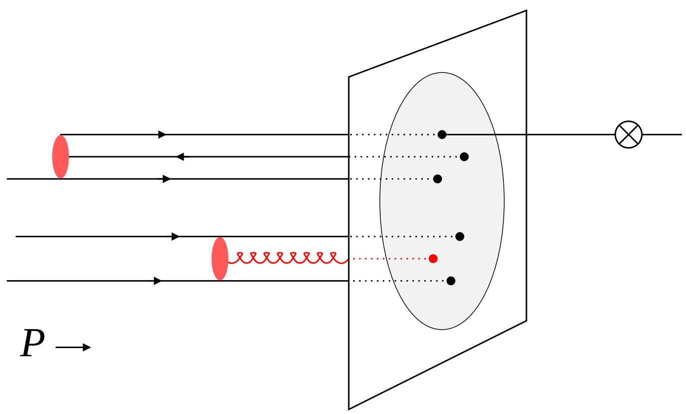
  Strong non-perturbative gluon fields
  Size $\ll 1\,\mathrm{fm}$. Lattice simulations, analytic models

  $\bar{q}q$ pair condensate, π as collective excitation
  Chiral symmetry breaking; Order parameter, Goldstone boson

- Slow–moving nucleon $P \sim \mu_{\mathrm{vac}}$

  $\langle N|\hat{O}|N\rangle$ from correlation functions

  No concept of particle content!
  Cannot separate "constituents" from vacuum fluctuations



- Fast–moving nucleon $P \gg \mu_{\mathrm{vac}}$

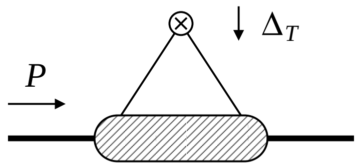
  Closed system: Wave function, Gribov, Feynman
  variable particle number, x_i, $\boldsymbol{k}_{Ti}$

  Longitudinal momentum densities: PDFs
  Transverse spatial distributions: Form factors, GPDs
  2nd quantized operator definitions: Renormalization, scale dependence

  Expresses low–energy dynamics!
  "Point of view"

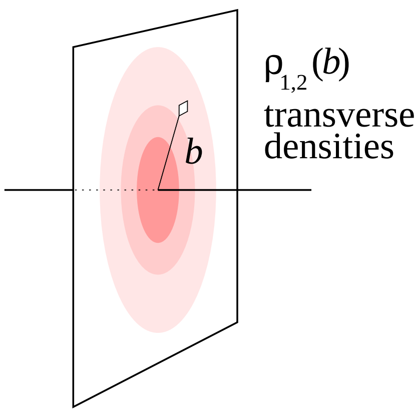
  High–energy processes take snapshot

Nucleon structure: Transverse densities



- Current matrix element parametrized by invariant form factors

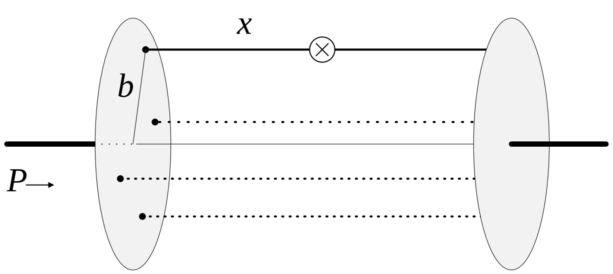
$$\langle N' | J_\mu | N \rangle \;\rightarrow\; F_1(t), F_2(t) \quad \text{Dirac, Pauli}$$



- Transverse densities $\quad t = -\boldsymbol{\Delta}_T^2$ Soper 76, Miller 07

$$F_{1,2}(t) \;=\; \int d^2b \; e^{i\boldsymbol{\Delta}_\mathrm{T}\boldsymbol{b}} \; \rho_{1,2}(b) \quad \text{2D Fourier}$$

Transverse density of charge and magnetization
$\boldsymbol{b}$ displacement from transverse C.M.



- Proper densities for relativistic systems

Overlap of wave functions with same particle nr
Breit frame distributions are not densities

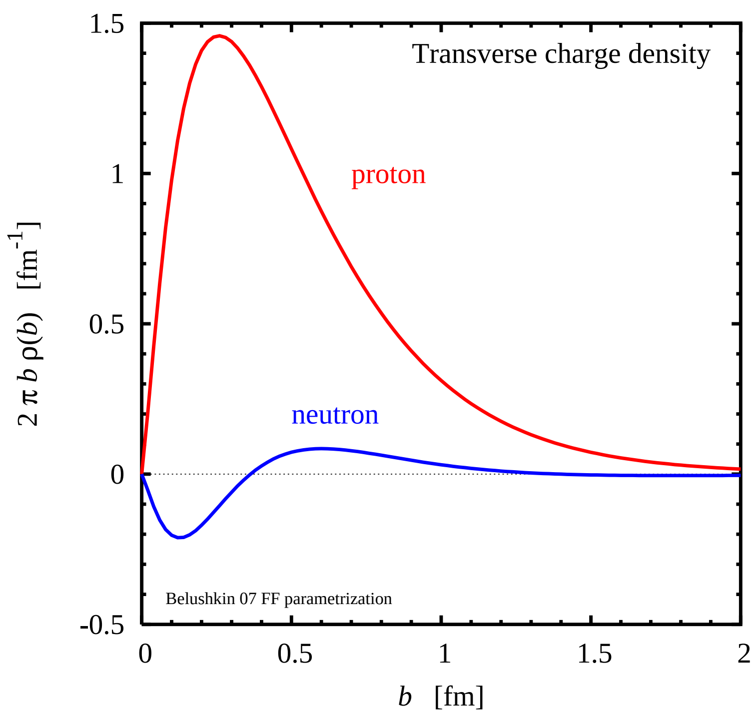
Spatial representation of relativistic system

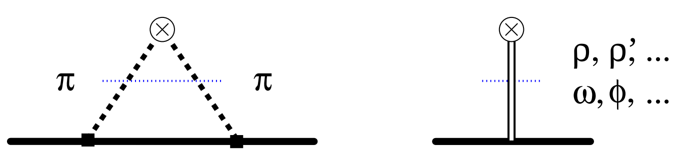
- Reduction of quark distributions GPDs

$$\rho_1(b) = \sum_q e_q \int_0^1 dx \, [q(x,b) - \bar{q}(x,b)]$$

Relate elastic FFs to QCD quark/gluon structure

Nucleon structure: Empirical densities





- Empirical transverse densities from spacelike form factor data

  Experimental and incompleteness errors estimated Venkat, Arrington, Miller, Zhan 10

  Recent low– and high–$|t|$ data incorporated
  MAMI: Vanderhaeghen, Walcher 10. JLab Hall A Riordan et al.

  Many interesting questions: Neutron, flavor structure, charge vs. magnetization

- Meson exchange picture

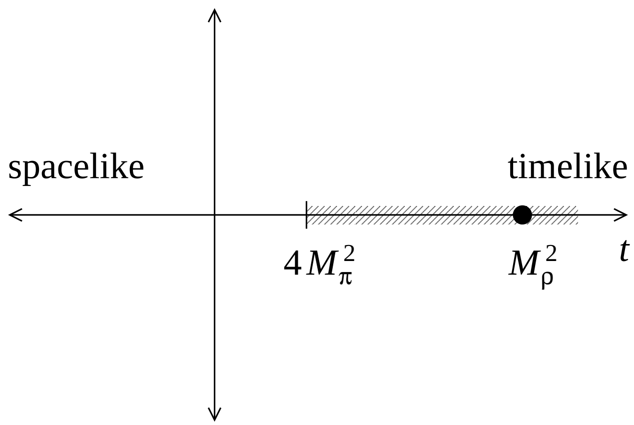
  Current couples to nucleon via hadronic exchange mechanism
  Relativity, causality: Analyticity, crossing invariance

  Sucessful phenomenology: Vector dominance
  Cf. NN interaction parametrization Bonn potential

  Relate to parton picture — quantitatively!

  VMD expressed in QCD D.o.F
  New insight into partonic structure
  Parton–hadron duality in t–channel

Spectral analysis: Dispersion representation

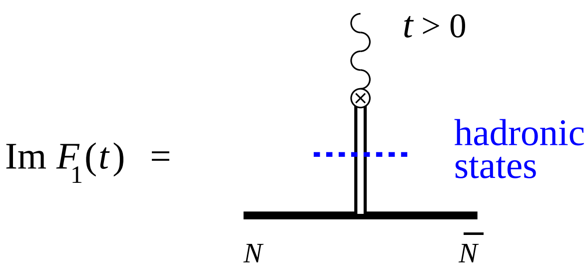


- Dispersion representation of form factor

$$F_1(t) \;=\; \int\limits_{4\mathrm{m}_\pi^2}^{\infty} \frac{dt'}{t' - t - i0} \, \frac{\mathrm{Im}\, F_1(t')}{\pi}$$

Spectral function $\mathrm{Im}\, F_1(t')$ describes "process"
current $\rightarrow$ hadronic states $\rightarrow$ $N\bar{N}$

$\mathrm{Im}\, F_1(t')$ from form factor fits and theory:
χPT near threshold, dispersion rels, pQCD $t \rightarrow \infty$



Isovector: $\pi\pi,\; \rho,\; \rho',\; \ldots$
Isoscalar: $\omega,\; \phi,\; K\bar{K},\; \ldots$

- Transverse density

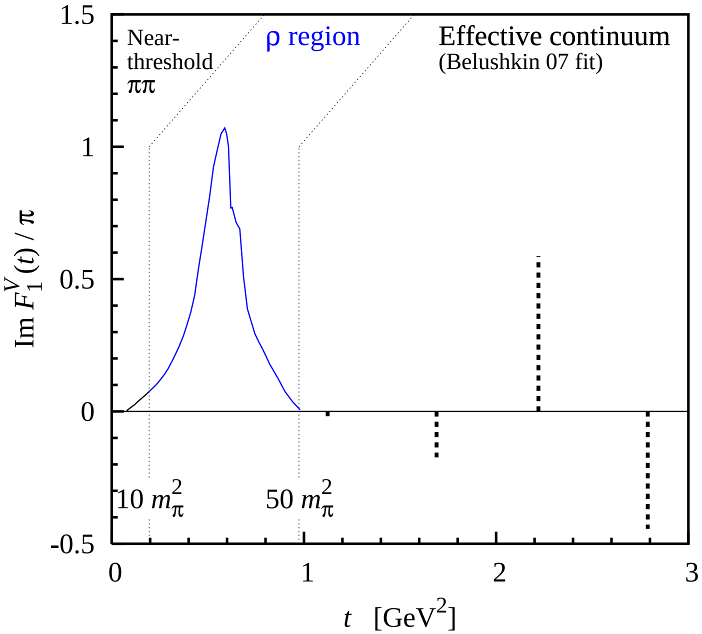
$$\rho(b) \;=\; \int\limits_{4m_\pi^2}^{\infty} \frac{dt}{2\pi^2}\, K_0(\sqrt{t}b)\; \mathrm{Im}\, F_1(t)$$

$K_0 \sim e^{-b\sqrt{t}}$ exponential suppression of large t

Distance b selects masses $\sqrt{t} \sim 1/b$: "Filter"
Cf. Borel transformation in QCD sum rules. Strikman, CW 10

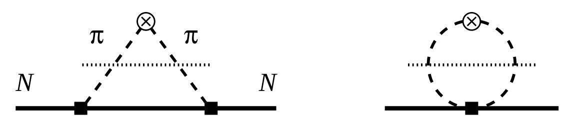
Peripheral $\rho(b) \longleftrightarrow$ Low–mass hadronic states

Spectral analysis: Isovector charge density



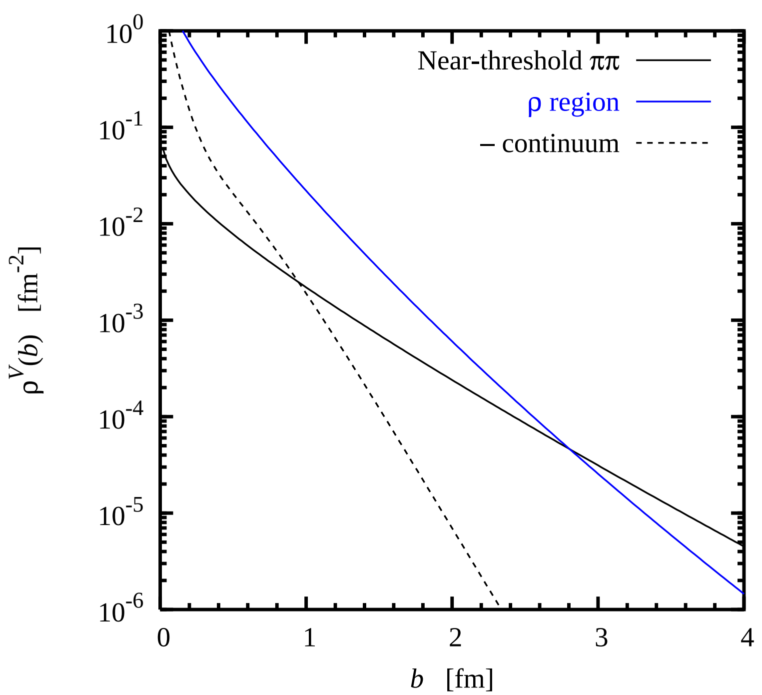
- Isovector spectral function

  Near–threshold $\pi\pi$ from chiral dynamics
  Universal, model–independent. Subthreshold singularity from N pole.
  χEFT: Becher, Leutwyler 99; Kubis, Meissner 00; Kaiser 03



  ρ region from dispersion analysis
  πN and $\pi\pi$ phase shifts. Höhler 76; Belushkin et al. 05

  High–mass continuum from form factor fits
  Belushkin, Hammer, Meissner 07. Update Lorenz et al. 12



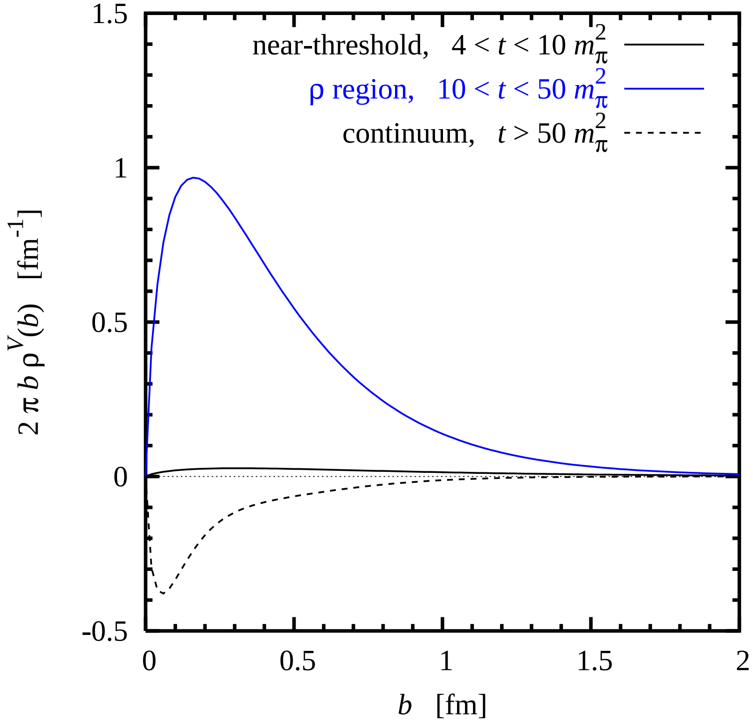
- Spectral analysis of isovector density

  Near–threshold $\pi\pi$ relevant only at $b > 2\,\mathrm{fm}$
  Surprisingly large distances!
  Peripheral density from χEFT. Strikman, CW 10; Granados, CW 13

  Intermediate $b = 0.5 - 1.5\,\mathrm{fm}$ dominated by ρ,
  only $\sim 10\%$ correction from higher states
  "Vector dominance" quantified in partonic picture

  Higher–mass states relevant only at $b < 0.3$ fm
  Average out at larger distances

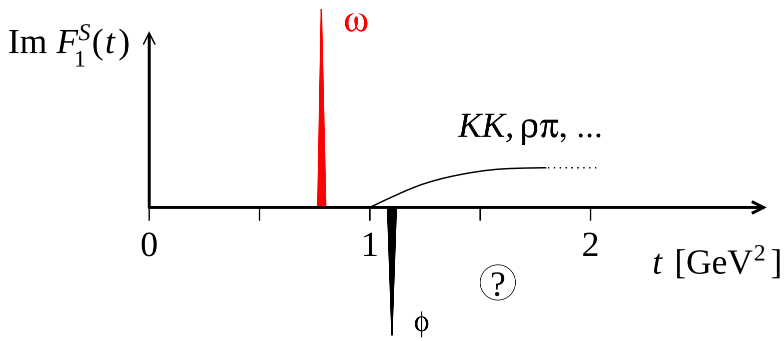
Spectral analysis: Isovector charge density

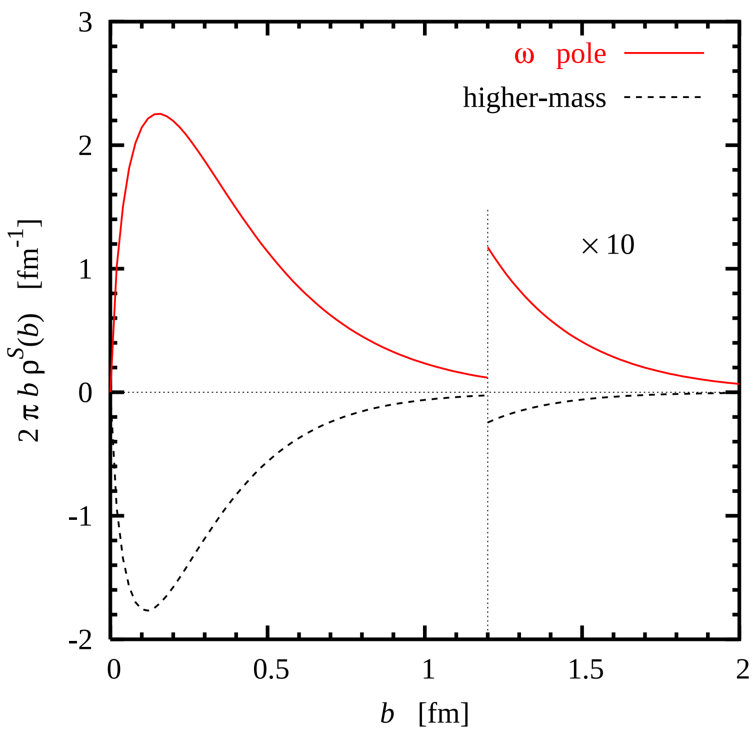


Radial charge density $2\pi b \rho^V(b)$
Area under curve gives total charge

Isovector transverse charge density at $b \sim 1\,\mathrm{fm}$ is dual to ρ meson exchange with 90% accuracy!

Spectral analysis: Isoscalar charge density





- Isoscalar spectral function

  ω exhausts strength below $1\,\mathrm{GeV}^2$
  Non-resonant 3π negligible

  Large negative strength above $1\,\mathrm{GeV}^2$, dynamical origin unclear
  ϕNN coupling $\leftrightarrow$ $s\bar{s}$ content of nucleon

  High–mass continuum from form factor fits
  Belushkin, Hammer, Meissner 07

- Spectral analysis of isoscalar density
  Miller, Strikman, CW 11

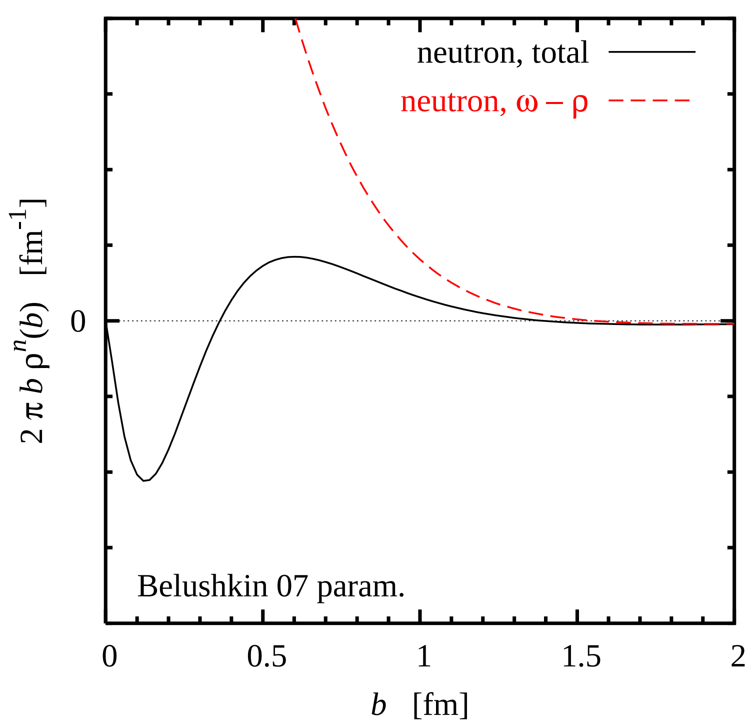
  ω dominates at $b > 1.5\,\mathrm{fm}$
  Fit uncertainty in ωNN coupling $\pm 15\%$

  Large cancellations between ω and higher–mass states at $b = 0.5 - 1\,\mathrm{fm}$

- Impact of future form factor data

  Sensitivity to ωNN coupling broadly distributed at spacelike $|t| \lesssim 1\,\mathrm{GeV}^2$
  Does not require measurements at extemely small $|t|$

Spectral analysis: Neutron charge density



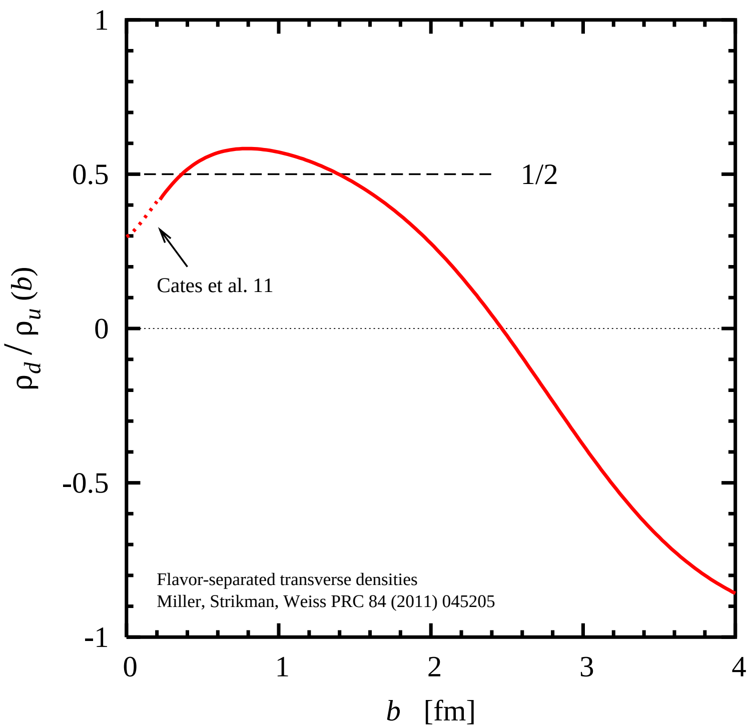
- Spectral analysis of neutron density

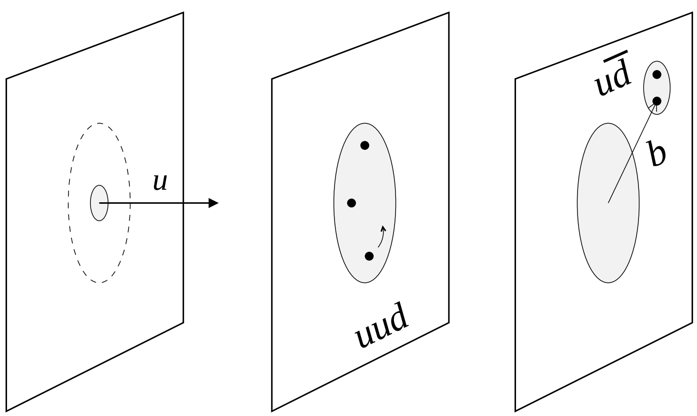
  $\omega - \rho$ alone gives large positive density!

  Substantially reduced by higher–mass states in isoscalar spectral function

  Neutron form factor measurements can help to determine isoscalar spectral function $\rightarrow$ ϕNN coupling, $s\bar{s}$ in nucleon

Parton interpretation: Quark densities





extreme $x \to 1$ configurations

mean−field motion of valence quarks

peripheral πn configurations

- Transverse densities of u and d quarks
  Constructed from FF fits. Small b from JLab Hall A Cates et al. 11

$$\rho_u(b) = \int_0^1 dx \, [u(x,b) - \bar{u}(x,b)] \ \text{etc.}$$

- Ratio ρ_d/ρ_u for interpretation

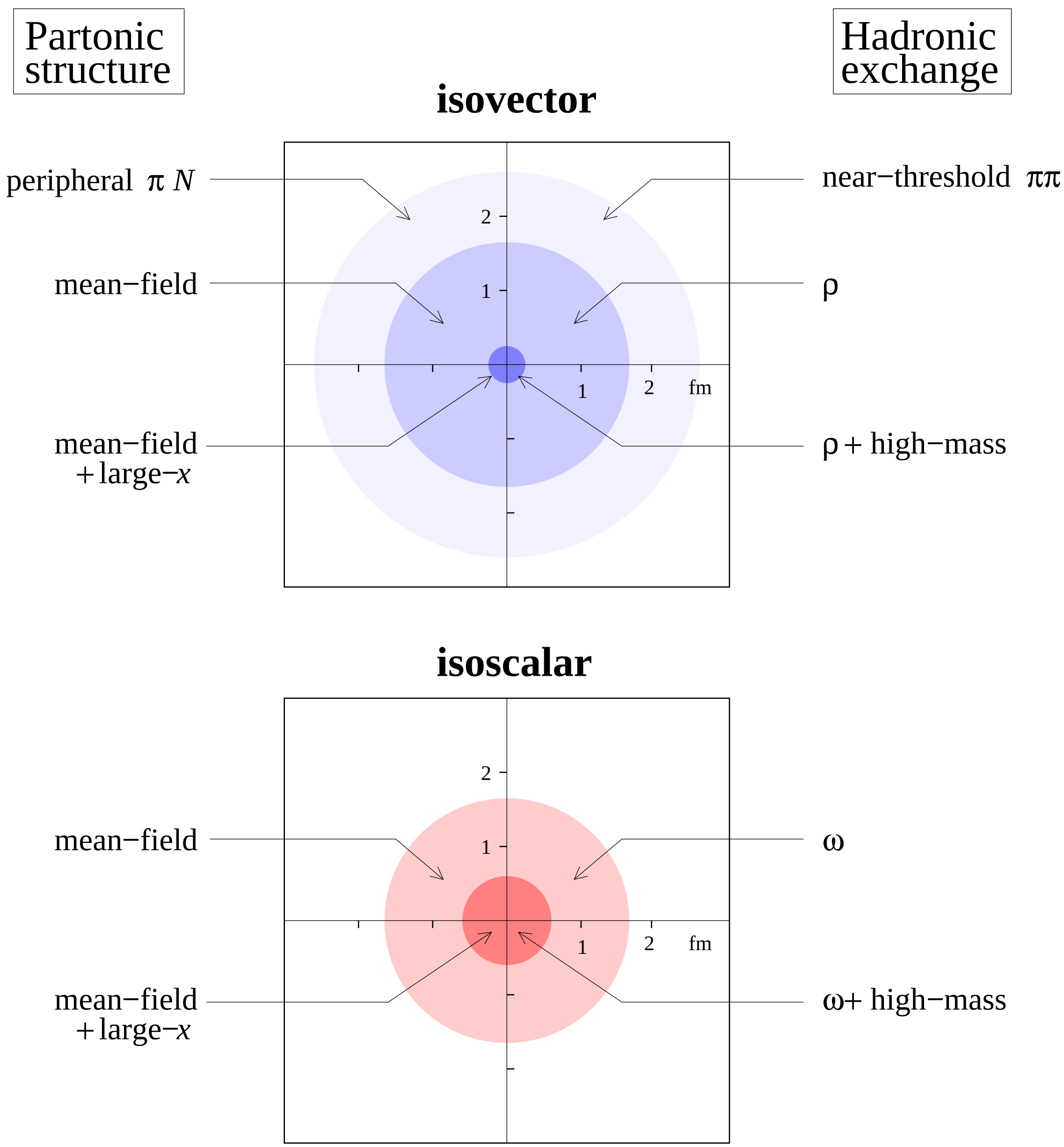
  Large b: $\rho_d/\rho_u \to -1$
  Peripheral πN configs in nucleon WF
  Equivalence of invariant and light–cone χPT: Strikman, CW 10
  Same configs govern chiral contributions to PDFs: Strikman, CW 09
  Many interesting theoretical issues!

  Intermediate $b \sim 0.3 - 1\,\text{fm}$: $\rho_d/\rho_u \sim 1/2$
  Mean-field motion of valence quarks
  Cf. Quark model, large–N_c QCD

  Small $b < 0.3\,\text{fm}$: $\rho_d/\rho_u < 1/2$
  Extreme $x \to 1$ configs where $u \gg d$
  PDF fits, pQCD counting

- Model–independent insights into partonic structure!

Parton interpretation: Duality



Disks indicate "region of dominance" of the various configurations/exchanges

- Parton–hadron duality explored locally in transverse space

  Model–independent, quantitative statements

  Benchmarks for dynamical model calculations

Parton interpretation: Much more information

- Pauli FF

  Transverse distribution of spin–dependent current

  $\rho_2(b) = \sum_q e_q \int_0^1 dx\ [e_q(x,b) - e_{\bar{q}}(x,b)]$ nucleon helicity–flip GPD

- Axial and pseudoscalar FFs

  Transverse distribution of axial and pseudoscalar charge

  $\rho_A(b) = \sum_q \int_0^1 dx\ [\Delta q(x,b) + \Delta \bar{q}(x,b)]$ spin–dependent parton densities

  – Pseudoscalar FF has π pole: Longest–range component of nucleon structure

- Energy–momentum tensor FFs

  Transverse distribution of momentum and matter

  Second moments of GPDS $\int_0^1 dx\ x\ [q(x,b) + \bar{q}(x,b)]$ etc.

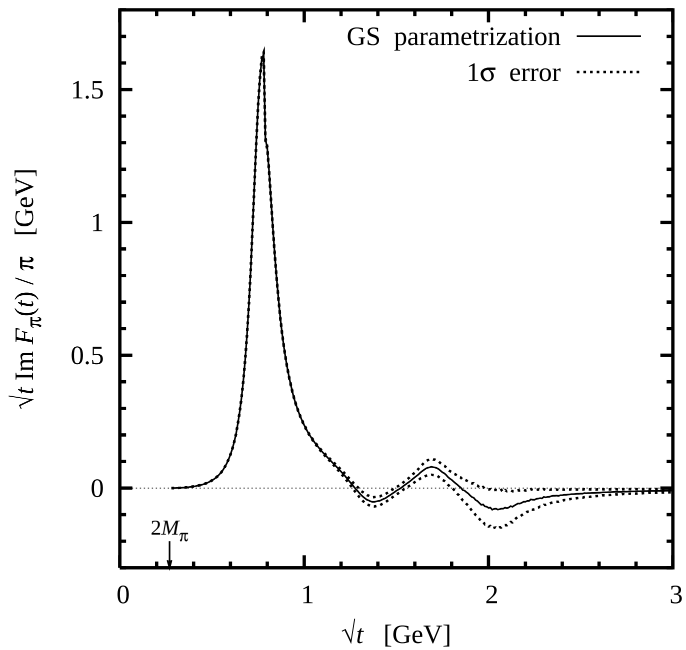
  C–even exchange: σ

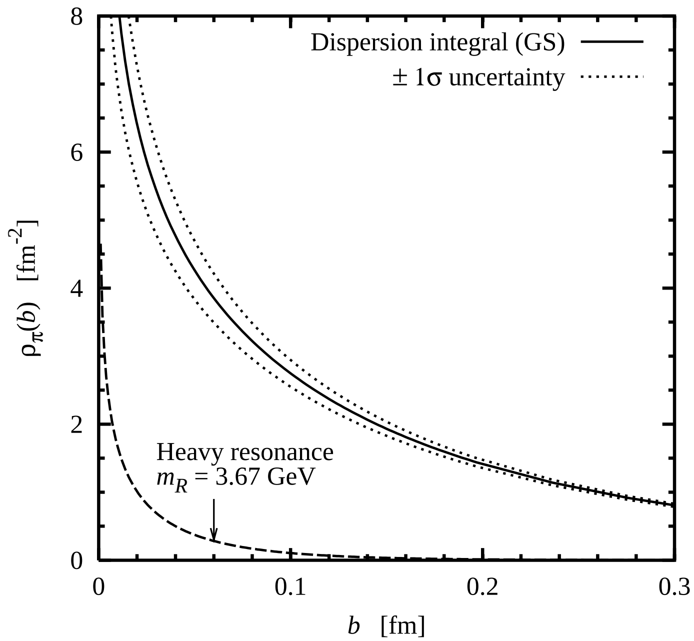
- x–dependent form factors: GPDs

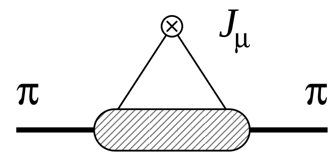
  Unify concepts of parton density and elastic FFs

  Probed in high–Q^2, low–t exclusive processes:
  Deeply virtual Compton scattering $N(e, e'\gamma)N'$, meson production $N(e, e'M)N'$
  HERMES, COMPASS, JLab. Extensive program planned with JLab 12 GeV and future EIC. Analysis challenging!

Pion: Transverse density from timelike data







- Spacelike FF poorly known at $|t| > 1\,\mathrm{GeV}^2$
  Electroproduction on nucleon, model-dependent. JLab Hall C 6/12 GeV

- Timelike FF from e^+e^- annihilation

  $|F_\pi|^2$ from cross secn, phase from models/theory

  Resonance–based parametrization from fit to data
  Bruch, Khodjamirian, Kuhn 04. CLEO 05 results not included.

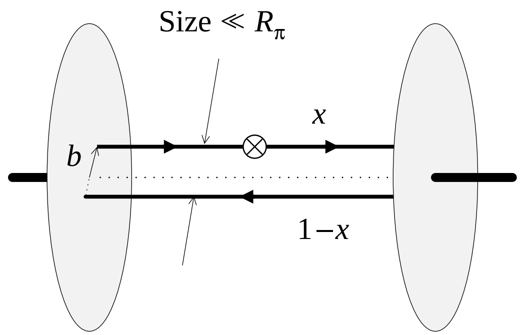
- Transverse density from dispersion integral
  Miller, Strikman, CW 10

$$\rho_\pi(b) \;=\; \int_{4m_\pi^2}^{\infty} \frac{dt}{2\pi^2}\; K_0(\sqrt{t}b)\;\mathrm{Im}\,F_\pi(t)$$

  Fully calculable, precise, error estimates

  Singular charge density at center of pion

Pion: Parton interpretation



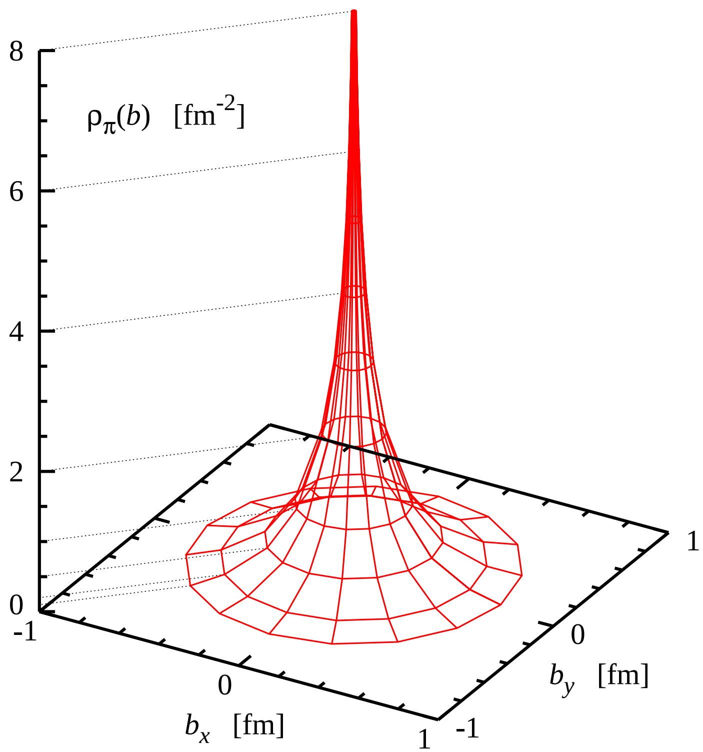
- Singular charge density at center due to point-like configurations in pion wave functr

  Configs of size $r \ll R_\pi$, mostly elementary $q\bar{q}$

  Observable in other high–momentum transfer processes: $\gamma^*\gamma \to \pi^0$, $\pi + A \to 2\,\text{jets}, \ldots$
  Universal property

  Large–size configurations with $x \to 1$ at scales $Q^2 > 1\,\mathrm{GeV}^2$ cannot account for empirical charge density at $b \to 0$
  Miller, Strikman, CW 10

  Detailed modeling with light–cone wave functions in progress



- 2D image of fast–moving pion

  First accurate transverse image based on data!

Summary: Theory

- Transverse densities connect partonic structure with hadronic spectrum

  Fully quantitative, consistent with QCD

  New approach to quark–hadron duality in t–channel

- Dispersion integral for $\rho(b)$ samples spectral function at masses $\sqrt{t} \sim 1/b$

  Systematic study of exchange mechanisms

  Mathematical properties: Asymptotic behavior, error analysis, . . .

- Nucleon charge density at intermediate distances $b = 0.5 - 1.5\,\text{fm}$ governed by vector mesons

  Chiral component relevant only at $b > 2\,\text{fm}$

  Origin of isoscalar strength beyond ω still unclear

- Pion charge density from timelike form factor data

  Precise 2D image with controlled accuracy

  Singular charge density at center attributed to pointlike $q\bar{q}$ configurations

Summary: Experiment

- Can the chiral component be studied experimentally?

  Effect on low–Q^2 form factors? Lorenz et al. 12

  CLAS/PRIMEX 12 GeV measurement at $10^{-4} - 10^{-2}\,\mathrm{GeV}^2$ PR12-11-106 Gasparian et al.

  Test fundamental χPT predictions!

  Affects extrapolation to $Q^2 \to 0$

- Dispersion fits to form factors provide much more information than Q^2–dependent parametrizations

  Should be updated with expected JLab 12 GeV data!

  Analyticity essential for studying nucleon's periphery

- Neutron form factor data crucial for determining isoscalar spectral function

  Impact on $s\bar{s}$ content of nucleon